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# Frequency Assignment for Joint Aerial Layer Network High-Capacity Backbone

**by Peng Wang and Brian Henz**

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*Computational and Information Sciences Directorate, ARL*

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**14. ABSTRACT**

The Joint Aerial Layered Network (JALN) could provide crucial communication links when milsatcoms are degraded or lost. Two-way traffic through a link is assigned to 2 disjoint frequency bands. Frequency Division Multiplexing Access (FDMA) is used to share bandwidth and avoid the interference among multiple transceivers on a single aerial platform. Two Frequency Assignment Problems (FAPs) are considered in this work, which are called MMC-FAP and MS-FAP. MMC-FAP is to minimize the frequency usage of the most congested aerial platform while accommodating the offered traffic demands and without violating the frequency constraints. MS-FAP is to minimize the frequency span in both frequency bands. By exploiting problem-specific properties, MMC-FAP can be formulated as a Mixed Integer Linear Programming (MILP) problem, which has a tight constraint space by explicitly finding all maximal cliques in the conflict graph. Then, binary search strategy is used to find an optimal solution to the MS-FAP problem while MMC-FAP occurs as a subproblem. Numerical experiments are used to show the performance of the proposed approach.

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## 1.  Introduction

The United States is reliant upon space assets for many different things, such as voice communications, data routing back and forth, command and control assets, intelligence assets, Global Positioning System data forwarded from ships to aircraft and to people on the ground. A potential nightmare for combatant commanders is a "day without space". In this scenario, a peer or near-peer competitor severely limits US forces' access to military communication and navigation spacecraft through jamming or something more destructive, such as antisatellite weapons. A concept called the Joint Aerial Layered Network (JALN), an Earth-based system, is hopefully moving into the realm of supplying an alternative to total reliance on space assets. JALN could provide crucial communication links when milsatcoms are degraded, or lost. Also, JALN provides a persistent, IP-based High-Capacity Backbone (HCB) aerial infrastructure and communication access to the joint forces that extend communications across the battlefield from an airborne platform.

One challenge for JALN is the resource management problems involving multiple antennas per aerial platform, limited available bandwidth and geometric blockage involving the body of the aircraft and antenna radiation pattern. Each JALN aircraft has $4$ mounting points for directional antennas, and they have different blockage patterns because of the airplane frame. One isssue is that how these antennas are assigned to JALN HCB links to maximize the link availability across the aerial backbone. The antenna assignment problem is formulated as a Mixed Integer Linear Programming (MILP) problem[1,2] where the objective function is to maximize the link availability of the worst link. A greedy approach[1] is proposed to find a suboptimal solution, and an efficient iterative approach[2] is proposed to find an optimal solution.

Another resource allocation consideration is the Frequency Assignment Problem (FAP), which has been widely studied over the past decades; there are numerous fruitful results that can be leveraged to this work. The considered waveform uses frequency separation between the forward and return links, for example, the return link must operate in the $14.40 - 14.83$ GHz band, and the forward link must operate in the $15.15 - 15.35$ GHz band. The total offered spectrum bandwidth for the aerial network is 200 MHz in forward and return spectrum, respectively. Frequency Division Multiplexing Access (FDMA) is used to share 200-MHz bandwidth and avoid

the interference among multiple transceivers on a single aerial platform.

Compared with traditional FAPs, there are 2 key differences for this specific FAP:

- Traffic from Node $A$ to Node $B$ could be transmitted in forward or return band for JALN while uplinks and downlinks use fixed-frequency bands for cellular networks.

- A 2-way traffic through a link could use different data rates and occupy different bandwidths due to different traffic demands or path losses. The traditional FAP assumes that uplinks and downlinks occupy the same bandwidth or same number of channels.

There are 2 FAPs considered for JALN HCB. The first FAP problem, called MMC-FAP, is to minimize the frequency usage of the most congested aerial platform in both forward and return bands while accommodating the offered traffic demands and without violating the frequency constraints. By exploiting the problem-specific properties, the MMC-FAP is formulated as a MILP problem, which is NP-hard in the worst case. The solution specifies the channels and frequency band used by each directed JALN HCB link. The second FAP problem, called MS-FAP, is to minimize the frequency span in both frequency bands. An iterative approach based on binary search strategy is developed to find an optimal solution of MS-FAP while MMC-FAP occurs as a subproblem. Only a feasible solution of MMC-FAP instead of an optimal solution will be obtained at each iteration, which significantly reduces the computational complexity. Numerical experiments are used to show the performance of the proposed method.

The remainder of this work is organized as follows. Section 2 briefly introduces the background of the FAP problem. In Section 3, problem definition is given, and MMC-FAP is formulated as a MILP problem. Then, an iterative approach is developed to find an optimal solution of MS-FAP. Section 4 shows the results from numerical experiments. Finally, concluding remarks are given in Section 5.

## 2. Background

FAPs have been widely studied over the past decades. We focus on Fixed Channel Assignment (FCA) where the set of connections remains stable over time. Graph theory was widely used for FAPs, and the relation of the FAP with the T-coloring problem was investigated. Andreas et al.[3] give an overview of the evolution of FAP from graph coloring and its generation to the models now used.

Mathematical optimization techniques are widely used modeling methods for FAPs. The basic FAP consists of assignment constraints, interference constraints, and an objective. All models share similar structures such as the assignment of frequencies and handling of interference. A feasibility-frequency assignment problem (F-FAP) arises when there is no objective to be optimized. If no feasible solution exists to F-FAP, the objective can be to find a partial solution that assigns as many frequencies as possible, which is known as Maximum Service FAP (Max-FAP). When feasible solutions exist to F-FAP and the objective is to minimize the number of used frequencies, the model is called the Minimum Order-FAP (MO-FAP). Another realistic objective is to minimize the span of the frequencies chosen (i.e., the difference between the highest and lowest frequencies used). This variant is called the Minimum Span-FAP (MS-FAP). MO-FAP and MS-FAP usually have the same set of constraints and only differ by their objective functions. In general, the optimal solution of MS-FAP may not use the minimum number of frequencies and vice versa.

The solution methods for these models are divided into 2 categories. The first is using exact optimization methods to find the global optimal solution. The typical methods include branch-and-cut,[4] branch-and-price, and combinatorial enumeration and so forth, where lower bounding techniques are applied to accelerate the tree search. In general the models for FAPs are formulated as a Mixed Integer Programming Problem (MIP), which is NP-hard. Thus, the majority of research papers are on heuristic methods to find suboptimal solutions with tractable computation complexity. The heuristic methods include local search (simulated annealing and tabu search), genetic algorithm, neural networks, constraint programming, and ant colony algorithm. The survey for FAPs can be found in Aardal et al. and Katzela and Niaghshineh.[5,6]

## 3. Frequency Assignment

Consider a JALN network with $n$ JALN nodes and $L$ directed links where each JALN node incidents up to $k$ directed links. The return link must operate in the $14.40 - 14.83$ GHz band, and the forward link must operate in the $15.15 - 15.35$ GHz band. FDMA is used to share 200-MHz bandwidth in both forward and return bands and avoid the interference among multiple transceivers in a JALN node.

### 3.1 Notation and Data Mode Selection

Let $\Phi$ be a set of concurrent sessions, and each session $\phi$ represents a source-destination pair in the network. A traffic demand $d_\phi$ for session $\phi$ has to be transmitted from the source node $\phi_s$ to the destination node $\phi_d$. Here, only single path routing is considered. Thus, a flow is confined to a single path, where the path for flow $\phi$ is $P(\phi)$. Using this notation, the total data rate sent over link $x$ is $\sum_{\{\phi | x \in P(\phi)\}} d_\phi$, where $\{\phi | x \in P(\phi)\}$ is the set of flows that cross link $x$. We define $O(n)$ and $I(n)$ as the sets of links that are outgoing from and incoming to node $n$. All links are directed; bidirectional communication between 2 nodes is represented by 2 directed links whose frequencies are assigned from forward and return bands, respectively.

Let $S$ be the set of available data modes for JALN nodes where each mode $s$ associates with the data rate $R_s$, the occupied bandwidth $B_s$ and the corresponding coding schemes, and so forth. We use $f \in \{F, R\}$ to denote forward or return bands. Time is divided into slots of unit size. Link $x$ can transmit at data mode $s$ in frequency band $f$ during time slot $t$ if it satisfies

$$SINR_x^f(t) \geqslant SINR_s, \tag{1}$$

where $SINR_x^f(t)$ is the Signal to Interference and Noise Ratio (SINR) at the receiver side of link $x$ for frequency band $f$, and $SINR_s$ is the required $SINR$ threshold for data mode $s$. Note that the values of $SINR_x^f(t)$ are usually different for forward and return bands because of different channel losses. One flight loop of all JALN nodes spans $T$ time slots. Then, data mode $s$ is feasible for link $x$ in frequency band $f$ if it satisfies

$$\frac{\sum_{t=1}^{T} \mathbf{1}_{\left\{SINR_x^f(t) \geqslant SINR_s\right\}}}{T} \geqslant \alpha, \tag{2}$$

where $\mathbf{1}_{\left\{SINR_x^f(t)\geqslant SINR_s\right\}}$ is the indicator function and $\alpha$ is the threshold that denotes the percentage of time that link $x$ achieves the data mode $s$ in frequency band $f$.

Given the traffic demand over link $x$ as $\sum_{\{\phi|x\in P(\phi)\}} d_\phi$, link $x$ must support the data rate $R_s \geq \sum_{\{\phi|x\in P(\phi)\}} d_\phi$. Due to limited spectrum resource, we select the data rate with minimum bandwidth for each directed link that accommodates the required traffic demand. A simple example can help us understand the data mode selection for JALN. The network shown in Figure 1 contains $3$ nodes and the traffic demands among nodes are as follows:

$$Flow1 : N1-> N2 : 50Mbps \tag{3}$$
$$Flow2 : N2-> N1 : 90Mbps$$
$$Flow3 : N2-> N3 : 140Mbps$$
$$Flow4 : N3-> N2 : 80Mbps.$$

For simplicity, we assume that the data rate is equal to the occupied bandwidth for this example: $S_i, i = 1, 2, ...$ denotes the selected data mode, and $B$ denotes the occupied bandwidth. The concept of logical link arises in data rate selection, and logical link $x_{s,f}$ denotes that link $x$ is transmitting with data mode $s$ in frequency band $f$. Since the traffic can be transmitted in forward or return bands, $2$ logical links are generated for each flow, and $8$ logical links in total are shown in Fig. 1. Thus, one logical link $x_{s,f}$ from each frequency band is selected for link $x$ and must satisfy

$$x_{s,f} = \arg\min_{s\in S}(B_s) \text{ where } R_s \geq \sum_{\{\phi|x\in P(\phi)\}} d_\phi; f = F \text{ or } R. \tag{4}$$

Now associated with link $x$ is either the logical link $x_{s,F}$ or the logical link $x_{s,R}$ or
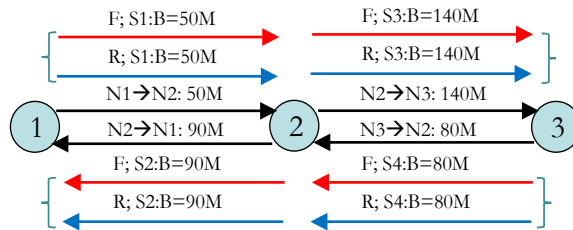


**Fig. 1  Data mode selection for 3-nodes network**

both.

## 3.2 Frequency Assignment Problem

The frequency band is usually partitioned into a set of channels, all with the same bandwidth $\delta$ of frequencies. The available set of channels denoted by $C = \{1, ..., N\}$ is available to all physical nodes. If more than one frequency band is available, each band has its own set of consecutively numbered channels. In this work, the forward and return bands have the same bandwidth and the same number of channels denoted by $C$. The concept of logical link adapts to new context. A logical link may occupy one or consecutive channel blocks in terms of its data mode. Then, the logical link $x_{s,i}^f$ denotes that link $x$ transmits with data mode $s$ and occupies the set of consecutive channels that start from channel $i$ in frequency band $f$. Assume that $s^{th}$ data mode occupies $m$ consecutive channels. A physical link with $s^{th}$ data mode in frequency band $f$ can be represented as $N - m + 1$ logical links between the same pair of physical nodes where each logical link starts from a different channel as shown in Figure 2. Let us assume that 200 MHz in both forward and return bands are partitioned into 20 channels with the channel bandwidth of 10 MHz. Then, each logical link shown in Figure 1 can be further represented as multiple logical links shown in Figure 2.
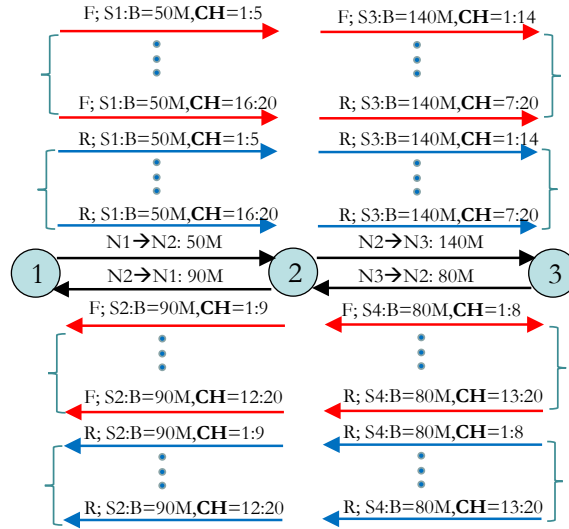


**Fig. 2 Logical links for FAP of 3-nodes network**

Let $\chi\left(x_{s,i}^f\right)$ be the set of logical links that are in conflict with $x_{s,i}^f$, i.e., $y_{t,j}^g \in \chi\left(x_{s,i}^f\right)$ if simultaneous transmissions over logical link $x_{s,i}^f$ and logical link $y_{t,j}^g$ are

not possible. The set of conflicting logical links, $\chi\left(x_{s,i}^f\right)$, is defined as:

$$\chi\left(x_{s,i}^f\right) = \{y_{t,j}^g \,\big|\, x \cap y \neq \emptyset \; and \tag{5}$$

$$f == g \; and$$

$$[i, i + \lceil \frac{B_s}{\delta} \rceil] \cap [j, j + \lceil \frac{B_t}{\delta} \rceil] \neq \emptyset\,,$$

where the first condition means that these 2 logical links share one common end, the second condition means that both logical links are in the same frequency band, and the third condition means that channels assigned to these 2 logical links overlap. Two logical links are in conflict if 3 conditions are satisfied simultaneously. No 2 logical links from the same physical link are allowed to be active simultaneously.

We define an *assignment* to be a vector $\mathbf{v} = \begin{bmatrix} v_1 & \cdots & v_{\tilde{L}} \end{bmatrix}$ for the network with $\tilde{L}$ logical links, where $v_{x_{s,i}^f} \in \{0,1\}$ with $v_{x_{s,i}^f} = 1$ implying that logical link $x_{s,i}^f$ is active during assignment $\mathbf{v}$. Then, an assignment specifies which links are transmitting, their data-rate modes, and the occupied channels that started from channel $i$ in frequency band $f$. The data rate across logical link $x_{s,i}^f$ during assignment $\mathbf{v}$ is denoted by $R_s$, and the required bandwidth for link $x_{s,i}^f$ is denoted by $B_s$ where the frequency band is denoted by $f$. Let directed links $x$ and $y$ represent the bidirectional communication between 2 neighboring nodes.

Given the traffic demand over link $x$ as $\sum_{\{\phi | x \in P(\phi)\}} d_\phi$, the MMC-FAP problem is to minimize the frequency usage of the most congested aerial platform in both forward and return bands while accommodating the traffic demands and without violating the interference constraints. The solution of MMC-FAP specifies a set of logical links that can transmit simultaneously. If a constraint shown in eq. (6) is included in the optimization problem for every 2 logical links in conflict, the computational complexity is prohibitively expensive for networks with a large number of logical links.

$$v_{x_{s,i}^f} + v_{y_{t,j}^g} \leq 1 \text{ if } y_{t,j}^g \in \chi\left(x_{s,i}^f\right) \tag{6}$$

Provided with the problem-specific properties, the set of maximal cliques can be explicitly constructed by applying the following:

- Fact 1: Each physical link has exactly one active logical link.

- Fact 2: Among all logical links incident to a channel $i$, no more than one of them can be active.

The number of constraints is significantly reduced. The MMC-FAP problem can be described as a MILP.

$$\min \beta$$

$$\text{subject to:} \sum_{\{x_{s,i}^f \in x\}} v_{x_{s,i}^f} = 1 \text{ for link } x \tag{7}$$

$$\sum_{\{x_{s,i}^f \in x;\, f=F\}} v_{x_{s,i}^f} + \sum_{\{y_{t,j}^f \in y;\, f=F\}} v_{y_{t,j}^f} = 1 \text{ for } x, y \tag{8}$$

$$-\sum_{\{x_{s,i}^f \in x\}} R_{x_{s,i}^f} \cdot v_{x_{s,i}^f} \leq - \sum_{\{\phi \mid x \in P(\phi)\}} d_\phi \text{ for link } x \tag{9}$$

$$\sum_{\substack{\{x_{s,i}^f \in O(n) \cup I(n); \\ f=F\}}} B_{x_{s,i}^f} \cdot v_{x_{s,i}^f} \leq \beta B_F^{Total} \text{ for node } n \tag{10}$$

$$\sum_{\substack{\{x_{s,i}^f \in O(n) \cup I(n); \\ f=R\}}} B_{x_{s,i}^f} \cdot v_{x_{s,i}^f} \leq \beta B_R^{Total} \text{ for node } n \tag{11}$$

$$\sum_{\substack{\{x_{s,i}^f \in O(n) \cup I(n); \\ i \in B(x_{s,i}^f)\}}} v_{x_{s,i}^f} \leq 1 \text{ for node } n \text{ at channel } i \tag{12}$$

$$v_{x_{s,i}^f} \in \{0, 1\}, \beta \in [0, 1].$$

where Constraint (Eq. 7) enforces that one logical link must be active for each physical link $x$, Constraint (Eq. 8) enforces that 2-way traffic must operate in different bands. Here one logical link in forward band must be active for either link $x$ or reverse link $y$, Constraint (Eq. 9) means that each physical link $x$ must accommodate the traffic demands, and Constraints (Eq. 10) and (Eq. 11) enforce the total bandwidth requirements for both forward and return bands. Constraint (Eq. 12) enforces that no more than one logical link can be active for all logical links sharing one common channel $i$ at node $n$, where $i \in B(x_{s,i}^f)$ denotes that channel $i$ is occupied by logical link $x_{s,i}^f$. A feasible solution of MMC-FAP must satisfy the following 2 conditions:

- Two-way traffic through a link must be transmitted in different frequency bands.

- Channels used at each platform must have no conflict for both forward and return bands.

Note that there is no feasible solution if $\beta$ is greater than $1$.

The introduction of logical links results in an Integer Programming problem that is an order of magnitude larger than the network size. The number of variables is $\mathbf{O}(|E||L||C|)$ and the number of constraints is $\mathbf{O}(|E||n||C|)$ where $|E|$ denotes the number of frequency bands, $|L|$ denotes the number of directed links, $|n|$ denotes the number of aerial platforms, and $|C|$ denotes the number of channels in frequency band as we assume that both frequency bands have same number of channels.

## 3.3   Minimum Span Frequency Assignment Problem

Given the assumption that both frequency bands have the same number of channels that are available to all platforms, the MS-FAP problem is to Minimize the frequency Span while accommodating the offered traffic demands without violating the frequency constraints. An iterative approach is proposed to find an optimal solution for MS-FAP. The idea is as follows: given a set of available channels, the MMC-FAP problem is used to find a feasible solution instead of an optimal solution. If a feasible solution exists, the set of available channels is reduced to half and we go back to solve MMC-FAP again. In other words, binary search is used to find the minimum span of the MS-FAP problem, and MMC-FAP occurs as a sub-problem. At each iteration only a feasible solution instead of an optimal solution is found for subproblem MMC-FAP.

Integer Programming solver is applied directly to find a feasible solution for every subproblem. Nowadays, all commercial MILP solvers combine cutting plane method with branch-and-bound (called branch-and-cut) to find the optimal solution. Here we point out that only one feasible solution instead of an optimal solution is needed for each subproblem. Specifically, we use the Integer Programming solver $intlinprog$ from Matlab to find a feasible solution. $MaxNumFeasPoints$ is an option for $intlinprog$ which specifies that the solver stops when it finds $MaxNumFeasPoints$ feasible solutions. Thus, we set $MaxNumFeasPoints = 1$, and $intlinprog$ stops after it finds a feasible solution. Finding a feasible solution

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is fast and usually only takes a few cuts because of the formulation of MMC-FAP.

## 4.  Numerical Experiments

To help understand the operations of JALN HCB, we first briefly introduce a scenario of small JALN HCB presented by Wang and Henz.[1,2] Then, we focus on studying the performance of the proposed approach for frequency assignment problems.

### 4.1  A Scenario of Small JALN HCB

#### 4.1.1  Experiment Setup

JALN HCB shown in Figure 3a consists of one Ground Entry Point (GEP) and $4$ JALN aircraft. There are $8$ directed JALN links in total, and traffic demands over directed links are generated from a uniform distribution of $[10, 50]$ Mbps. Figure 3b shows the geolocations of the GEP and the flight paths of $4$ JALN aircraft. The labels $'a, b, c, d'$ show the path direction of JALN aircraft. The tear-drop flight path starts at the middle, follows the labels, and then ends in the middle. For a better view, we artificially divide the tear-drop path into $5$ segments with different colors. All JALN aircraft are synchronized.
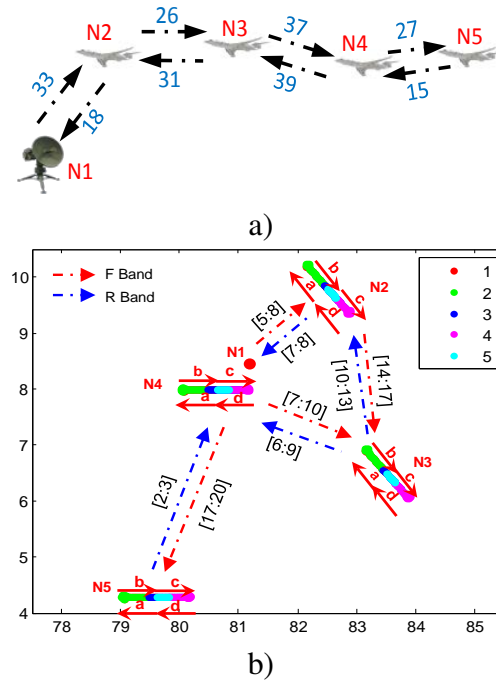


a)



b)

**Fig. 3  a) JALN HCB 5 node scenario, and b) frequency assignment solution for MMC-FAP**

Each JALN aircraft is equipped with up to 4 transceivers that share the bandwidth by using Frequency Division. Then, each transceiver at JALN aircraft associates with a directional antenna. Four antennas are mounted at top-front, bottom-front, bottom-rear of fuselage, and top-rear of vertical stabilizer. Electromagnetic Modeling and Simulation (M&S) was used to model blockage due to the airframe, as well as fractional blockage. We refer the readers to the scenario of small JALN HCB presented by Wang and Henz[1] for details.

### 4.1.2 Solutions to MMC-FAP and MS-FAP

Traffic demands over directed links satisfy a uniform distribution of $[10, 50]$ Mbps. The total available bandwidth of 200 MHz is partitioned into 20 channels with the channel bandwidth of 10 MHz in both forward and return bands. The computations below were performed on a 2.6 GHz Intel Core(TM) i5-6440HQ processor with 16 GB RAM. Figure 3b shows the solution of MMC-FAP for this 5-node scenario. The red-dotted line denotes the forward band and the blue-dotted line denotes the return band. The solution satisfies the frequency assignment requirements: 2-way traffic through a link are assigned in different frequency bands and the frequency channels at each platform have no conflict for both frequency bands. Nodes $N2$, $N3$, and $N4$ are the most congested nodes, which use 8 channels in the forward band and node $N3$ uses 8 channels in the return band. The total number of channels used are 13 and 10 for forward band and return band, respectively. It is not efficient that the selected channels spread over the whole spectrum. Thus, MS-FAP is used to squeeze the channels to the minimum span.

Binary search strategy is used to find an optimal solution of MS-FAP, and the initial lower and upper bounds of bandwidth are set to $[10, 200]$ MHz. At each iteration MMC-FAP occurs as a subproblem and only a feasible solution instead of an optimal solution needs to be found. Figure 4a shows an optimal solution for MS-FAP, which uses 80 MHz bandwidth or 8 channels in both bands. Compared with the optimal solution of MMC-FAP, MS-FAP balances the traffic between the forward and return bands. Figure 4b shows the computation time of MILP solver to find a feasible solution at each iteration. The iterative approach takes 5 iterations to converge to an optimal solution. The bandwidths exploited by binary search are $[110, 60, 90, 80, 70]$ MHz. Blue diamond denotes a feasible solution and red "X" denotes an infeasible solution. The maximum computation time is around 0.19 s, and the total computation time over all iterations is 0.40 s. Overall, the computation

time decreases as less channels and less logical links are considered. This computation time does not include the overheads such as formulating the subproblem, and so forth.
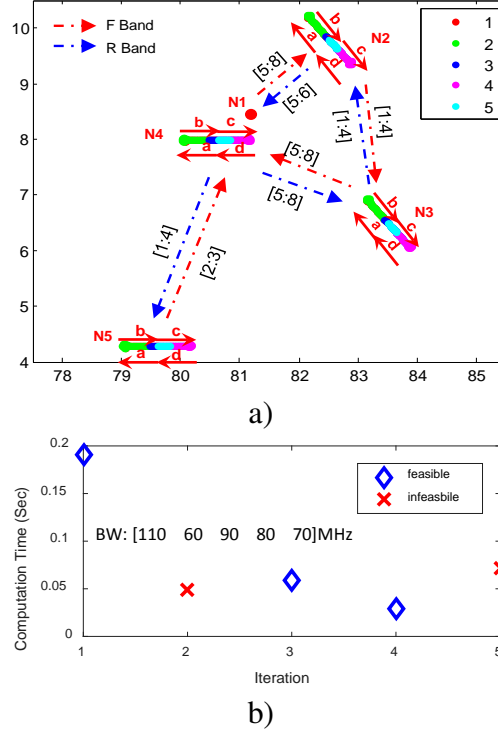


**Fig. 4** **a) Frequency assignment solution for MS-FAP, and b) computation time at each iteration**

## 4.2 JALN HCB - Grid Topology

### 4.2.1 Experiment Setup

It is difficult to generate a scenario including geographic location, force laydowns, JALN aircraft flight paths, and the geolocations and orientations of JALN aircraft at every second. To further study the performance of the proposed approach, we artificially construct a grid topology with $n \times n$ nodes, and the total numbers of directed JALN links is $4n(n-1)$. Traffic demands over directed links satisfy a uniform distribution of $[10, 50]$ Mbps.

### 4.2.2 MMC-FAP and MS-FAP for $6 \times 6$ Grid

Consider a grid topology with $6 \times 6$ nodes and $120$ directed JALN links. Figure 5 shows the solution of MMC-FAP for this $6 \times 6$ grid topology. Red denotes the forward band and blue denotes the return band. The total number of available chan-

nels is 20 for both bands. Nodes $[8, 10, 11, 16, 28, 29]$ are the most congested nodes that use 14 channels in the forward band. The total number of channels used are 20 for both forward and return bands. Also, the computation time to find an optimal solution is 4.46 s.
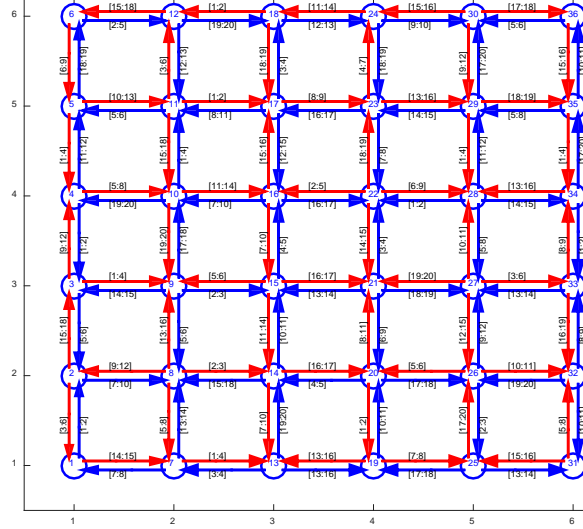


**Fig. 5  MMC-FAP for** $6 \times 6$ **grid**

Binary search strategy is used to find an optimal solution for MS-FAP and the initial lower and upper bounds of bandwidth are set to $[10, 200]$ MHz. At each iteration, MMC-FAP occurs as a subproblem and only a feasible solution instead of an optimal solution needs to be found. Figure 6a shows an optimal solution for MS-FAP, which uses 140 MHz bandwidth or 14 channels in both bands. Figure 6b shows the computation time of MILP solver to find a feasible solution at each iteration. The iterative approach takes 4 iterations to converge to an optimal solution. The bandwidths exploited by binary search are $[110, 160, 140, 130]$ MHz. The maximum computation time is around 2.69 s, and the total computation time over all iterations is 5.15 s.

## 5.   Conclusion

In this report, we study 2 frequency assignment problems for JALN HCB where 2-way traffic through a link uses 2 disjoint frequency bands. The first FAP called MMC-FAP is to minimize the frequency usage of the most congested aerial platform in both frequency bands while accommodating the offered traffic demands and
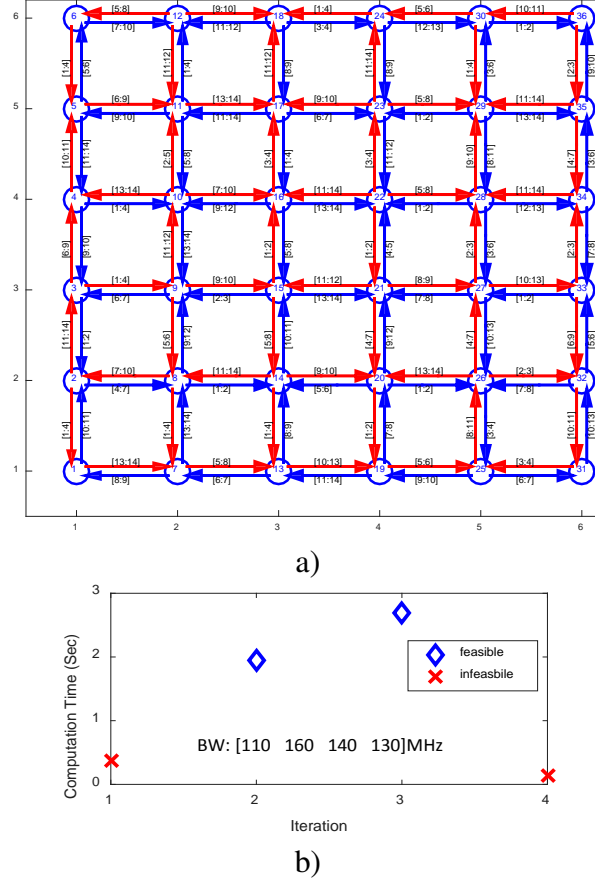
**Fig. 6 a) MS-FAP for** $6 \times 6$ **grid, and b) computation time at each iteration**

without violating the frequency constraints. By exploiting problem-specific properties, MMC-FAP is formulated as a MILP that provides a tight constraint space by explicitly finding all maximal cliques in the conflict graph. The second FAP called MS-FAP is to minimize the frequency span in both frequency bands. Binary search is used to find an optimal solution while MMC-FAP occurs as a subproblem. Only a feasible solution of F-FAP instead of an optimal solution needs to be found at each iteration.

# 6. References

1. Wang P, Henz B. Antenna assignment for JALN HCB. In: IEEE Milcom; 2015 Oct; Tampa, FL.

2. Wang P, Henz B. Efficient approach to find optimal antenna assignment for JALN HCB. In: IEEE Milcom; 2016 Nov; Baltimore, MD.

3. Eisenblätter A, Grötschel M, Koster A MCA. Frequency planning and ramifications of coloring. Discussiones Mathematicae Graph Theory. 2002;22(1):51-88.

4. Aardal K, Hipolito A, van Hoesel S, Jansen B. A branch-and-cut algorithm for the frequency assignment problem. Netherlands: Maastricht University; 1995. Report No.: 96/011.

5. Aardal KI, Van Hoesel SP, Koster AM, Mannino C, Sassano A. Models and solution techniques for frequency assignment problems. Annals of Operations Research. 2007;153(1):79–129.

6. Katzela I, Naghshineh M. Channel assignment schemes for cellular mobile telecommunication systems: A comprehensive survey. IEEE Personal Communications. 1996;3(3):10–31.

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## List of Symbols, Abbreviations, and Acronyms

| | |
|---|---|
| FAP | Frequency Assignment Problem |
| FCA | Fixed Channel Assignment |
| FDMA | Frequency Division Multiplexing Access |
| F-FAP | Feasibility FAP |
| GEP | Ground Entry Point |
| GPS | Global Positioning System |
| HCB | High Capacity Backbone |
| IP | Integer Programming |
| JALN | Joint Aerial Layer Network |
| Max-FAP | Maximum Service FAP |
| MILP | Mixed Integer Linear Programming |
| MIP | Mixed Integer Programming |
| MMC-FAP | Minimize the frequency usage of the Most Congested platform in both forward and return bands FAP |
| MO-FAP | Minimum Order FAP |
| MS-FAP | Minimum Span FAP |
| M&S | Modeling and Simulation |
| NP | Non-deterministic Polynomial-time |
| SINR | Signal to Inteference and Noise Ratio |

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